Fiber optic non-wearable respiratory monitoring based on in-line modal interferometer

Ying Shen[1,2], Wei Xu[3], Na Zhang[3], Shanhong You[1*], Changyuan Yu[2,4], Cheungchuen Yu[3]

1 School of Electronic & Information Engineering, Soochow University, Suzhou 215006, China
2 National University of Singapore (Suzhou) Research Institute, Suzhou 215123, China
3 Anlight Optoelectronic Technology Inc., Suzhou 215123, China.
4 Department of Electronic and Information Engineering, The Hong Kong PolytechnicUniversity, Kowloon, Hong Kong
shyou@suda.edu.cn

Abstract: A real-time non-wearable respiratory monitoring system based on single-mode-fiber-multimode-fiber-single-mode-fiber (SMS) with core-offset splicing is demonstrated and experimentally validated. Both the inhalation and exhalation activities can be detected within a wide respiratory frequency range.

OCIS codes: (060.2370) Fiber optics sensors; (120.3180) Interferometry; (170.3890) Medical optics instrumentation

1. Introduction

Respiratory is a physiological parameter, which is important to not only patients, but also the healthy people. For humans, this process results in air containing oxygen being inhaled into the lungs, where gas exchange occurs across the alveolar-capillary membrane. Respiratory rate is a vital sign used to monitor the progression of illness, and the typical respiratory rate for a healthy adult at rest ranges from 12 to 20 per minute [1].

Over the past few decades, fiber optic sensors have attracted growing attention in applications for respiratory monitoring, because of their intrinsic advantages of simple structure, inexpensive fabrication costs, fast response and immunity to electromagnetic interference. For example, Y. Zhu et al [2] proposed a method for reliable respiratory rate estimation for fiber bragg grating (FBG) optical sensor arrays by introducing signal quality estimation, but it still has limitations owing to the cost and complicated algorithm. X. Li et al [1] proposed a SMS structure based respiratory sensor which was attached to a thin plastic film in an oxygen mask. However, the Thor Labs S5FC 1550P broadband optical source is used in the experiment, which results in expensive monitoring setup.

In this paper, we present a simple and non-wearable respiratory monitoring sensor based on SMS structure with 900-micron buffer jacket, which avoids fragility in practical use. The proposed structure is capable of distinguishing different types of respiratory conditions including normal, slow and urgent respiratory state.

2. Sensing principle

The proposed structure is fabricated by splicing a section of multimode fiber (MMF) into two sections single mode fibers (SMFs), as shown in Fig. 1. At each splicing point, there is a slight core-offset.

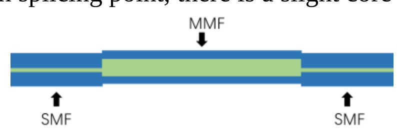

Fig. 1. Schematic diagram of the SMS structure.

As described, when incident light enters the lead-in SMF, only the LP_{01} mode exists. At the first SMF-MMF spliced point, the light is coupled into MMF and then high-order core modes of the MMF are excited [3]. At the second MMF-SMF spliced point, the interference between different modes occurs. Finally, these modes are coupled back into the lead-out SMF. If only considering two dominant modes, the phase difference ψ between the two dominant modes can be given as [3]:

$$\psi = \frac{2\pi}{\lambda}(n_{ex1} - n_{ex2})L = \frac{2\pi}{\lambda}\Delta n_{eff}L \quad (1)$$

where λ is the central wavelength, n_{ex1} and n_{ex2} represent the effective refractive indices of two modes participating in the interference.

The transmission intensity can be written as:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}cos\psi \quad (2)$$

When the human subject lies on this structure, the respiratory process causes some micro-strain, which changes the ψ. Then the transmission intensity I changes accordingly. So we choose to monitor the power variations to show the different types of respiratory conditions.

3. Experiments and discussions

The configuration of the SMS combining with the core-offset fiber structure is fabricated by a commercial fiber splicer (Fujikura FSM-80S). The SMF is of the standard size 8.2/125μm, and the core/cladding diameters of the step index fiber MMF is 62.5/125μm. The length of MMF is about 8m, and the core-offset is about 3μm. The structure is fixed on a mouse-mat-like thin cushion and placed on the surface of the bed mattress. The subject can lie on the cushion and make sure the back is in contact with it for measurement. In the experiment, we use an optical spectrum analyzer (OSA) to find the appropriate operating wavelength firstly. The transmission spectrum of the SMS structure is shown in Fig. 2, and the appropriate center wavelength of laser light source is 1548nm. The laser light source through SMS connects to the photodiode (PD) detection. The inhalation and exhalation cycles will result in different forces applied on the SMS structure which induce different bend radii, and hence different spectral responses are recorded by the PD. Then the electric signal is collected by data acquisition card and is sent to the computer for offline processing, as shown in Fig. 3.

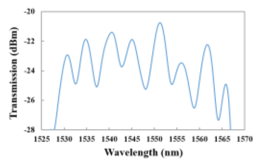

Fig. 2. The transmission spectrum of the SMS structure.

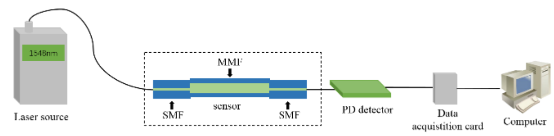

Fig. 3. Schematic diagram of the experimental setup.

The experimental results are shown in Fig. 4. The upper graph of Fig. 4 (a) illustrates the respiratory pattern for a normal respiratory state tested during 30s. Red line and blue line are the respiratory signals, which are monitored by SMS structure and traditional respiratory sensor, respectively. The filtered output signals of the raw respiratory are represented in the lower graph of Fig. 4 (a). It is clear from the Fig. 4 (a) that the proposed SMS structure can be easily and accuratly used for monitoring the normal respiratory process. Similarly, slow and urgent respiratory behaviors can also be tested, and their corresponding respiratory pattern are shown in Fig. 4 (b) and (c). It can be seen that the sensor can easily and effectively distinguish different respiratory states.

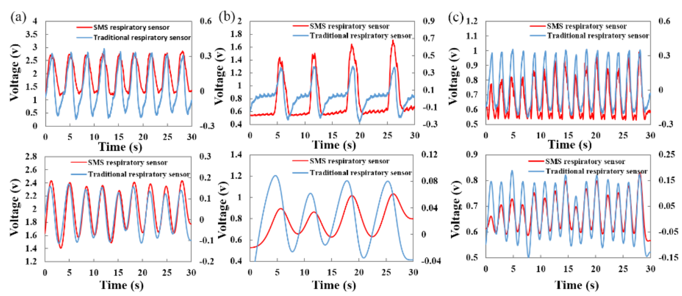

Fig. 4. (a) Normal, (b) slow and (c) urgent respiratory state: the upper graphs present the raw respiratory pattern, and the lower graphs present filtered output signals of the raw respiratory pattern

4. Conclusions

A simple optical fiber interference structure used as respiratory monitoring has been proposed and demonstrated in the paper. The structure has the absolutely attractive advantages, such as simple structure, easy to fabricate, low cost and fast response to the inhalation and exhalation process. It is non-wearable and non-invasive measurement without sacrificing the human subject's comfort. After testing the sensor, we observed that it can easily and effectively monitor different respiratory states in real time.

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